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# Zone Modelling and Visualisation: Keys to the Design of Low Carbon Buildings

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## Abstract

*A new approach to building modelling software, to support the iterative design of energy efficient buildings, is proposed. The proposal is for the combination of two, previously separate, software types - building design modelling and building performance simulation, along with the development of a third component - a design advisor, into one software tool. This software is intended for use by architectural practices, who may not have access to energy expertise, and who may then struggle to maintain design standards for non-domestic buildings required to satisfy rigorous energy performance regulations.*

*In this paper we describe, through an example, how the three components would work together, by the employment of zone meshes, to visualise, simulate and support with information and advice, the design of a building. The novelty of the method resides in the application of underlying zone meshes for the support of iterative building design. The approach is described, illustrated and future work outlined.*

**Keywords---Building Information Modelling [BIM], Energy, Climate Change, Building Performance Simulation [BPS] Building Energy Simulation [BES].**

## 1 Introduction

The reduction of carbon dioxide emissions through the decrease of energy consumption by buildings is now a critical task [1]. Governments around the world are legislating for new buildings that use significantly less energy than those already built in the days of cheap fossil fuels. Iterative, holistic building design is key to how architects will meet the challenges of designing beautiful, yet low energy buildings. Energy modelling, integrated within the design process, is seen as crucial to the optimization of the building [2]. Software has an important role to play in the support of this holistic approach to building design to achieve rigorous, high, energy usage standards in the buildings of the future [3].

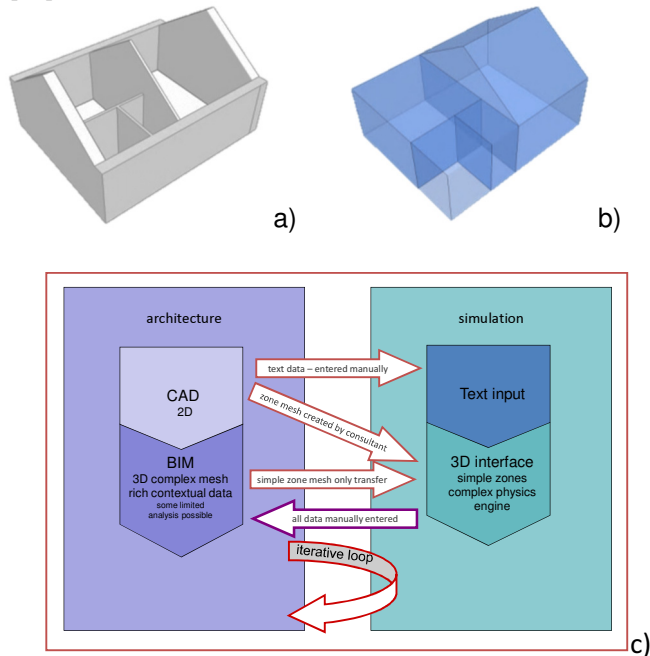
The need for creating buildings with very low energy demands may mean that architectural creativity may be compromised [4]. The ability to make easy use of BPS [Building Performance Simulation] could enable the architect to explore a range of design options whilst monitoring their implications on the predicted energy performance. The use of BPS at the present time is, however, limited [5]. It is often restricted to iconic projects where the budget is sufficiently large to enable the employment of specialist energy consultants. There is also concern about the knowledge required by building designers to implement low energy strategies [6]. Whilst low energy buildings have and are being built, they constitute a small proportion of all development and they will probably have benefited from significant input from energy consultants. In the future architects developers and owners will be required to reduce dramatically the energy used to build and run buildings. For instance in the UK **all** new buildings will be required to be zero carbon by 2019. Many architectural practices, especially small firms without access to energy expertise, will struggle to combine high design standards, especially for non-domestic buildings, with rigorous energy performance. This paper proposes new software that could integrate BES [Building Energy Simulation] into building design and make it more understandable and accessible to small practices with limited budgets.

The paper is organized as follows; the limitations of existing approaches are first discussed, the software proposal is introduced; the role of the zone to: 1) support iterative building design; 2) support BPS processes and 3) provide an information system is described and finally possible future work is outlined.

## 2 Existing approaches

The traditional separation of architectural design and energy simulation processes and the separate standalone software results in a dichotomous view of the building model [7]. The separate approaches are illustrated in Figure 1; the architectural view is of a building composed of objects such as walls, floors and roofs. The energy simulation view is that of zones; volumes of

thermally consistent air. Interoperability of data between the different types of software is limited and imperfect. The need to integrate design and building performance simulation software has been discussed in the literature for some time [8][9][10][11][12]. It is seen as a necessity to enable the replacement of traditional sequential processes with interactive concurrent design [13].



**Figure 1a) the architectural view of the building composed of objects b) the thermal view of the building composed of spaces and c) the current separate architectural and simulation approaches to software**

There have been significant developments towards integrated tools with the large software houses developing new or adapting existing software. For instance Autodesk's Project Vasari, Ecotect<sup>1</sup> and ArchiCAD's Eco Designer<sup>2</sup> have been developed for use in the early conceptual design phases by building designers. In general these tools use fairly simplified algorithms for thermal simulation calculations. In parallel, new and more user-friendly GUIs [Graphical User Interface], have also been developed for the more complex simulation engines such as EnergyPlus<sup>3</sup>. DesignBuilder<sup>4</sup>, Bentley System's AECOsim<sup>5</sup> and Hevacomp<sup>6</sup> and OpenStudio<sup>7</sup> are all examples of this approach.

<sup>1</sup><http://usa.autodesk.com/>

<sup>2</sup><http://www.graphisoft.com/products/ecodesigner/>

<sup>3</sup><http://apps1.eere.energy.gov/buildings/energyplus/>

<sup>4</sup><http://www.designbuilder.co.uk/>

<sup>5</sup><http://www.bentley.com/en-US/Promo/AECOsim/>

<sup>6</sup><http://www.bentley.com/en-US/Products/Building+Analysis+and+Design/Hevacomp.htm>

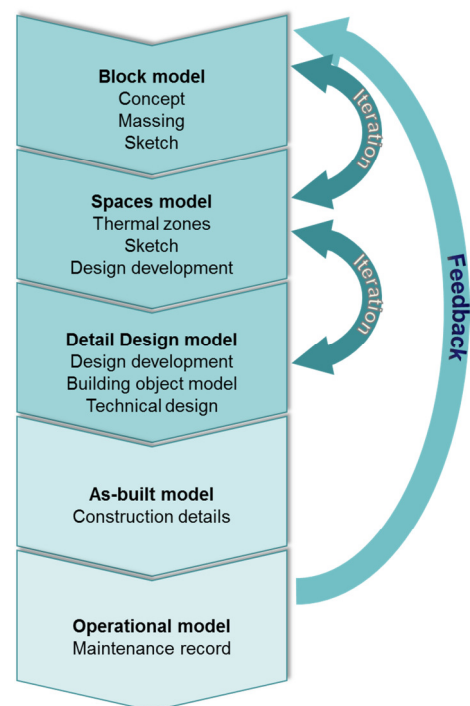
<sup>7</sup><http://openstudio.nrel.gov/>

For a comparison of tools for the design of Net Zero Energy Buildings see Attia and De Herde [6]. They conclude that there is a need for more investment in early design tools with the addition and improvement of many features, including informative support (pre-decision and post processing of simulation), optimization of renewable energy and access for architects to simulation software that model the physical processes rigorously.

However, the priorities of the dominant vendors appear to be on the development of energy analysis tools embedded within their flagship products with poor, or no, interoperability of data to external BPS or BIM software [7].

### 3 Combined software

The proposed software is planned to cover the lifespan of the building over five stages as shown in Figure 2. This paper concentrates on the first three stages, *block design*, *space design* and *detailed design*. The block design phase could also be called the concept, massing or sketch phase. It is when the overall shape (mass) and footprint of the building is determined. The space design phase covers the development of the building into individual spaces or thermal zones. This could also be called sketch or design development. The third stage of this proposal, when the design is developed, is called the detailed design.

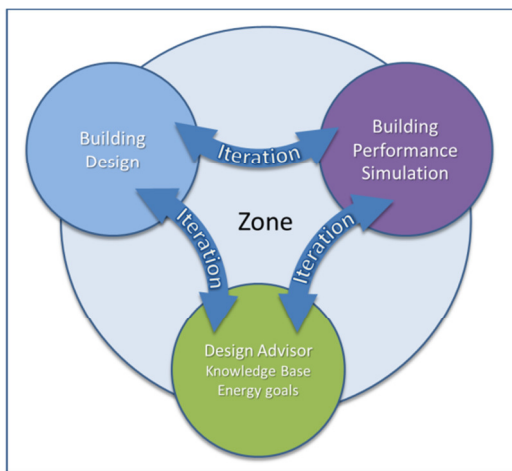


**Figure 2 The five stages for the software, this paper concentrates on the first three stages**

The last two stages are important; the *as-built model* is a record of the building as constructed, recording any modifications to the design as a result of changes on site. The *operational model* would facilitate the recording of data from POE [Post Occupancy Evaluation].

There are three separate components that the software proposal is required to provide:

- Building design functions with at least the existing (and sophisticated) features of BIM [Building Information Modelling] software
- Support for BESs, with either:
  - The algorithms written into the building design software
  - Acting as a GUI to BPS software installed on the same computer or network
  - Provide good interoperability of data for free standing BPS software
- A design advisor that would have two distinct features
  - A knowledge base
  - Targets and goal tracking.



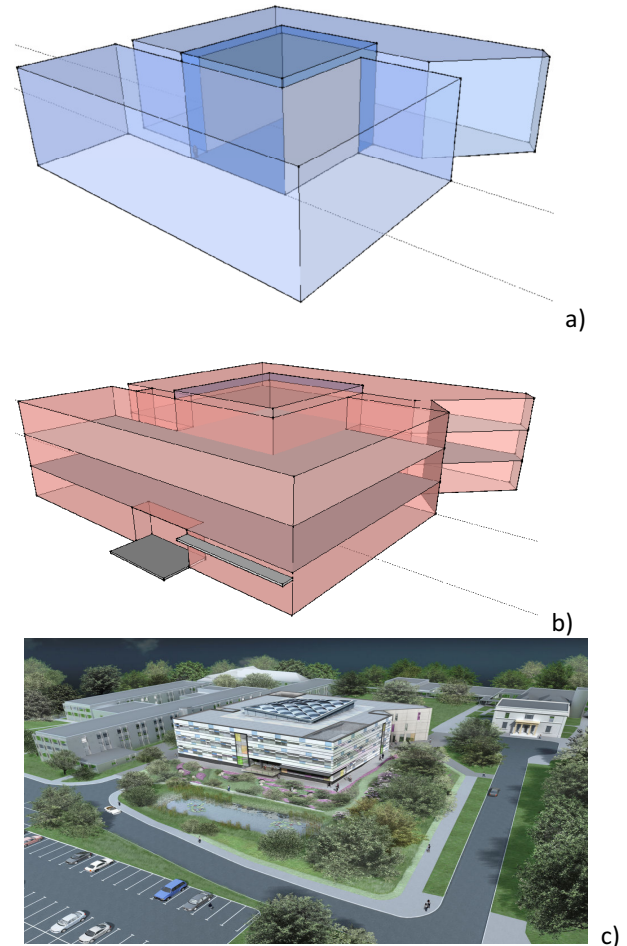
**Figure 3 The Zone mesh at the center of the iterative building design process. It facilitates the transfer of data between the 3 software components**

The three components of the software are shown in Figure 3. At the centre to this proposal is the concept of the 'zone' to support iterative design. The term zone is derived from the concept of the thermal polygon zone as employed in BPS. We use the term to describe a 3D planar mesh, composed of zero thick surfaces that enclose a volume of air. It is envisaged that the use of such a mesh will enable the iteration between the various design stages and support optimization of the building form, fabric and energy usage. The zone mesh would form the basis for BES and act as a frame for setting of energy goals and targets within the design advisor component of the software. The role that the zone mesh takes in the software is described in the following sections.

#### 4 The use of the zone throughout the building modelling stages

Architects are confident in working with spaces or zones [14][4]. The use of zones as a design medium is not new; it is used in Ecotect [15] and more recently in

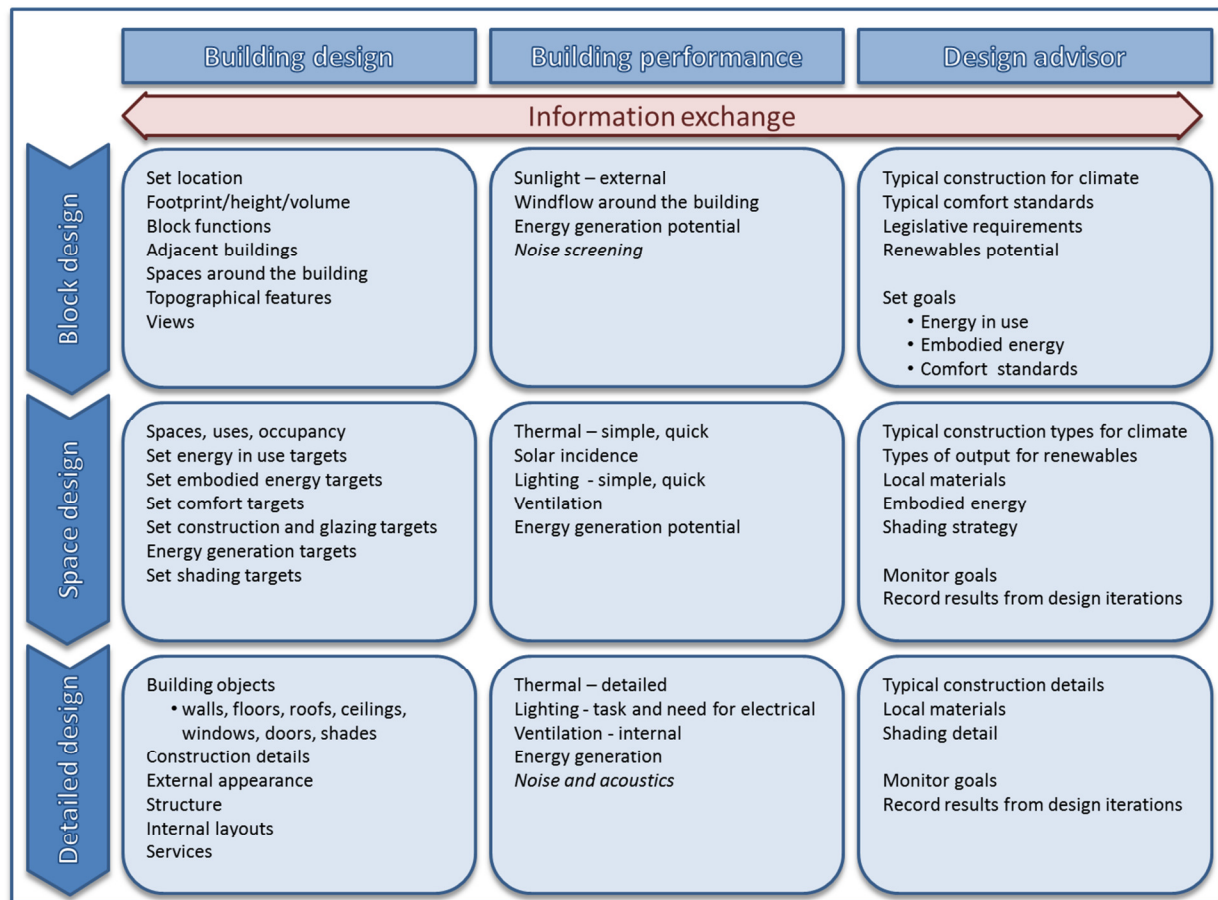
Project Vasari. However, where this proposal varies from these types of software, is that it extends past the early conceptual building design stage and is intended to act as the basis for iterative design throughout the life of building project.



**Figure 4 The different modelling stages in the building design process showing: a) Block design, the building as a number of blocks; b) Space design, the blocks broken down into a series of space zones and c) Detail design, the model with external finishes added<sup>8</sup>**

Iterative design, the ability move from the building conceptualisation to sketch and to detail phases and back again as required, is important in the design of low energy buildings. With this software it is proposed that the modelling process starts with blocks (zones/volumes). In the next phase these zones are subdivided into spaces (thermal or non-thermal zones). The zone (mesh) used to form the spaces is then used as a frame or skeleton used to attach the detailed objects of the building. The three stages are shown in Figure 4. This example is an existing building, the Jennie Lee, The Open University, Walton Hall, Milton Keynes.

<sup>8</sup>Figure 4 a) and b) modelled in Sketchup and c) used with permission of Swanke Hayden Connell Architects



**Figure 5 Matrix of building design, performance and design advisor activities set against the modelling stages of block, space and detailed design**

Fundamental to this approach is a building model mesh (the zone) composed of volumes enclosed by zero-thick planar surfaces. These volumes or zones act as a 'skeleton' or 'frame' for the building model to which building objects are applied, such as windows, doors and roofs, as shown in Figure 4 (c). This is a different approach to the current practice of either retro-fitting or completely re-modelling zones as part of a post-design energy analysis. As discussed earlier, there are dichotomous views of the building model. Architects start with simple sketch-type models that are developed into detailed views of the building, complete with moldings, profiles and structural elements. Although often the building concept has been simple, the building model becomes increasingly complex as the project is developed. Energy experts however require a simple building model. Dynamic energy modelling, because it typically simulates the response of a building to climate at hourly intervals over a year, is computationally demanding. The more complex the model mesh, the more time-consuming the simulation, with little improvement in the uncertainty of the simulation results [5]. BES and similar simulation and analysis tools require a 'simplified' or 'reduced' building geometry [16]. This method effectively retains the simplicity (and intelligence) of the architects original concept within the

building model and makes it visible and available for later simulation as if required.

The use of zones meshes would enable multi-criteria analysis through either:

- The integration of existing algorithms programmed within the building design software,
- The provision of a GUI to BES software such as EnergyPlus, installed on the same computer, network or linked via the Internet to a server,
- The provision of export and import of data to and from free standing BPS software, for instance CFD [Computational Fluid Dynamics]. CFD, employed for use in internal ventilation studies, is computationally very demanding and it can be difficult to interpret the results, as such it is considered too specialist to be included in this software.

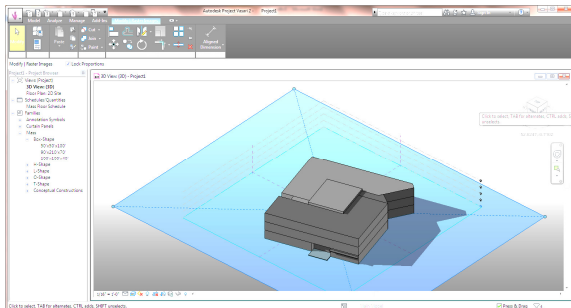
Building design is multi-faceted and involves different activities at different stages in the process, as shown in the matrix in Figure 5. The following sections discuss how the zone mesh is used to enable the combination of building design modelling, BES and design advisor functions.



## 4.1 The block design stage

At the block design stage the visualization of the building is of simple block zones as shown in Figure 4 a). The blocks would be generated from a palette of primitive volumes, which could be assembled and manipulated as required, with 'push-pull' of surfaces and vertices along with Boolean operations to combine volumes. The blocks could be coloured, translucent/transparent or wire-framed/solid as required. The principal rule is that surfaces between blocks would be co-planar and that the blocks are labelled.

The activities undertaken by the design team in the block design stage are given in Figure 5. The first action on any project is to set the building location which then fixes the climate. The effect of this is that the design advisor can give information on strategic options and types of construction appropriate for that region. The design activities undertaken in this phase include an analysis of the site; adjacent buildings, topographical features and potential views. The building function(s) can be set; this will trigger the design advisor to supply information regarding legislation and comfort standards. The design can then commence with visualisation of the concept as a group of blocks. With a simple building it might be one block; more complex projects may have multiple blocks and functions. These block zones can then have goals established, based on their footprint or volume. The goals could be for energy in use, embodied energy and comfort standards.



**Figure 6The space zone model used in a shadow analysis<sup>9</sup>**

Simulations can then be run for sunlight/shadows, such as shown in Figure 6, and windflow around the building. The aim of these early stage simulations are to identify, by means of a visualisation, any problems such as wind canyoning or permanent shadowing created by the block forms and/or adjacent buildings. The potential for the use of renewable energy can be established based on the available portion of the site area for GSHP [Ground Source Heat Pumps], incident solar energy for domestic hot water or electricity generation using PV [Photo Voltaic] and topographical features for wind turbine generation.

## 4.2 The space zone stage

The next stage in the design process, see Figure 5, is the subdivision of the blocks into spaces as shown by comparison of Figure 4 a) and b). The space zones should be volumes of air that are intended to have consistent thermal values.

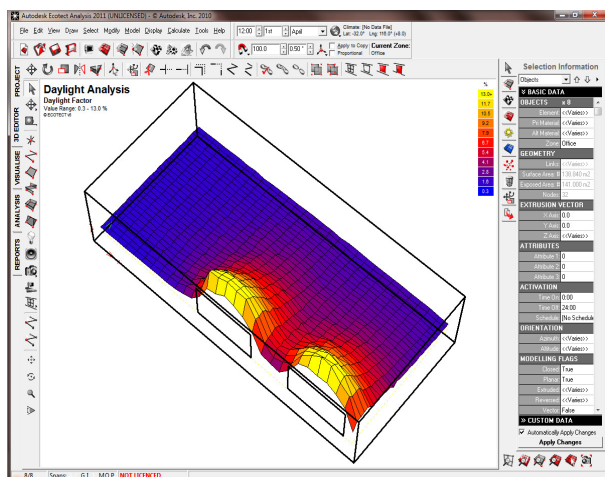
A typical visualisation of the zone mesh as a series of thermal spaces is shown in Figure 4 (b). This stage would be developed from the block zone, by splitting the blocks into a number of smaller units. This could be achieved automatically or by 'drawing' split lines. As with the block zone the appearance - colour, transparency, solid/wireframe options could be applied. In a very simple building the block and space zone could be the same. However, in most cases this will involve groups of rooms, for instance a row of offices on one floor. It could, however, be one room, if that was deemed to have a significantly different condition at different points, for instance on a corner of a building. Equally it could be part of a space, for instance, in a large, deep plan exhibition area that could be subject to varying thermal conditions due to the presence of windows along one wall. It has been argued that this definition of the thermal view of the building is better carried out by the building designer, rather than the current practice of an energy consultant, as they have a better understanding of the building [17]. This use of the concept of zones would also encourage the architect to visualize the building as a thermal unit in addition to other concerns such as structural, organizational and aesthetics. The software would include for more than one space zone type. A thermal zone is a mesh that denotes an enclosed space within the building, completely enclosed with floors, walls, ceilings, roofs and/or adjacent zones. Outside zones or spaces such as balconies and covered areas would be considered as non-thermal zones.

The space zone can then be used to 'attach' targets for energy, in-use and embodied, and set comfort standards. These targets could be part of the graphical display, possibly through a 'dashboard' panel, and be continually updated as the design is developed. Individual surfaces of the space zones could be selected within the model (highlighted) and targets set for construction, glazing, shading and PV/solar hot water. For instance the thermal resistance and thermal mass values of external walls and roofs could be set. The design advisor could be active in making suggestions at this stage. For instance, based on the orientation of the surface and the climatic data, it could advise on percentages of glazing, both in terms of heat loss/gain and any subsequent need for shading.

The range of planned simulations available at this stage are set out in Figure 5. Simulation and analysis would be rapid at this stage, comparable to the process of architectural sketching. This could be through the use of quick-to-run algorithms and enable 'what-if' scenarios to support the development and refinement of architectural concepts. Although the design advisor system might

<sup>9</sup>Figure 6 modelled in Project Vasari

recommend a percentage of glazing for thermal reasons, the location and proportion of windows would affect the quality of light in the building. Figure 7 shows a preliminary daylighting study carried out on one space. It shows the falloff of light from the windows and that different fenestration would be required to ensure a more even distribution of light. Thermal modelling could employ relatively simple algorithms such as those developed by ASHRAE<sup>10</sup> [American Society of Heating, Refrigerating and Air-Conditioning Engineers] or the CIBSE [Chartered Institution of Building Services Engineers] admittance method<sup>11</sup>. More detailed thermal modelling could be available at this stage, but it would be envisaged that it would be employed towards the end of the design iteration stage, and perhaps left to run overnight. Solar incidence data would be used to test out the need for shading and quantify the PV generation potential. Windflow studies would enable the development of a natural ventilation strategy.



**Figure 7 Daylight analysis of a space showing distribution through the space<sup>12</sup>**

Visualization of the simulation results at this early sketching of ideas stage is crucial. It requires comparison of the results with the goals and targets set within the design advisor component. At this stage the visualization could be very simple, aimed to illustrate how close the current design solution is to achieving a particular performance goal. Key, to the iterative building design process, is that the software should enable the designer to retrieve and compare previous design options/solutions and simulation results.

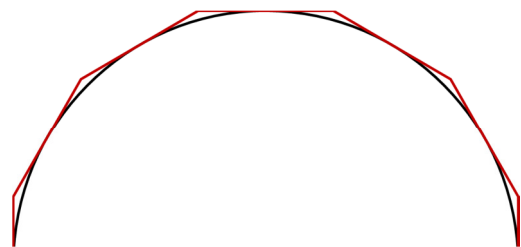
### 4.3 The detailed design stage

The detailed design stage involves using the space zone mesh as a frame or skeleton to which building objects are attached or located within. At this stage the

building objects represent 'real' building elements or products, such as external and internal walls, roofs, floors, ceilings, windows and doors as shown in Figure 4 (c). The space and block zone meshes created in the earlier stages are building objects and would be recorded as such in a software backend database. However, they should be regarded as a conceptual 'thing', similar in many respects to a setting out line on a building site.

Key to the software operation is a set of rules for the relationships of building objects within the building model. This affects the ownership, naming, positioning and connection of the building objects. A parent-child hierarchy would be employed whereby all 'real' building objects, such as external and internal walls, roofs, floors, ceilings, windows and doors are 'owned' by one named, space zone mesh.

As with many types of design and visualisation software there would need for the facility to place objects, such as the zone mesh, onto 'layers'. The feature would enable the isolation, visibility and manipulation of elements on a particular layer.



**Figure 8 The relationship between a curved surface and a planar zone mesh. The curve is 'attached' to the flat surface at a tangent.**

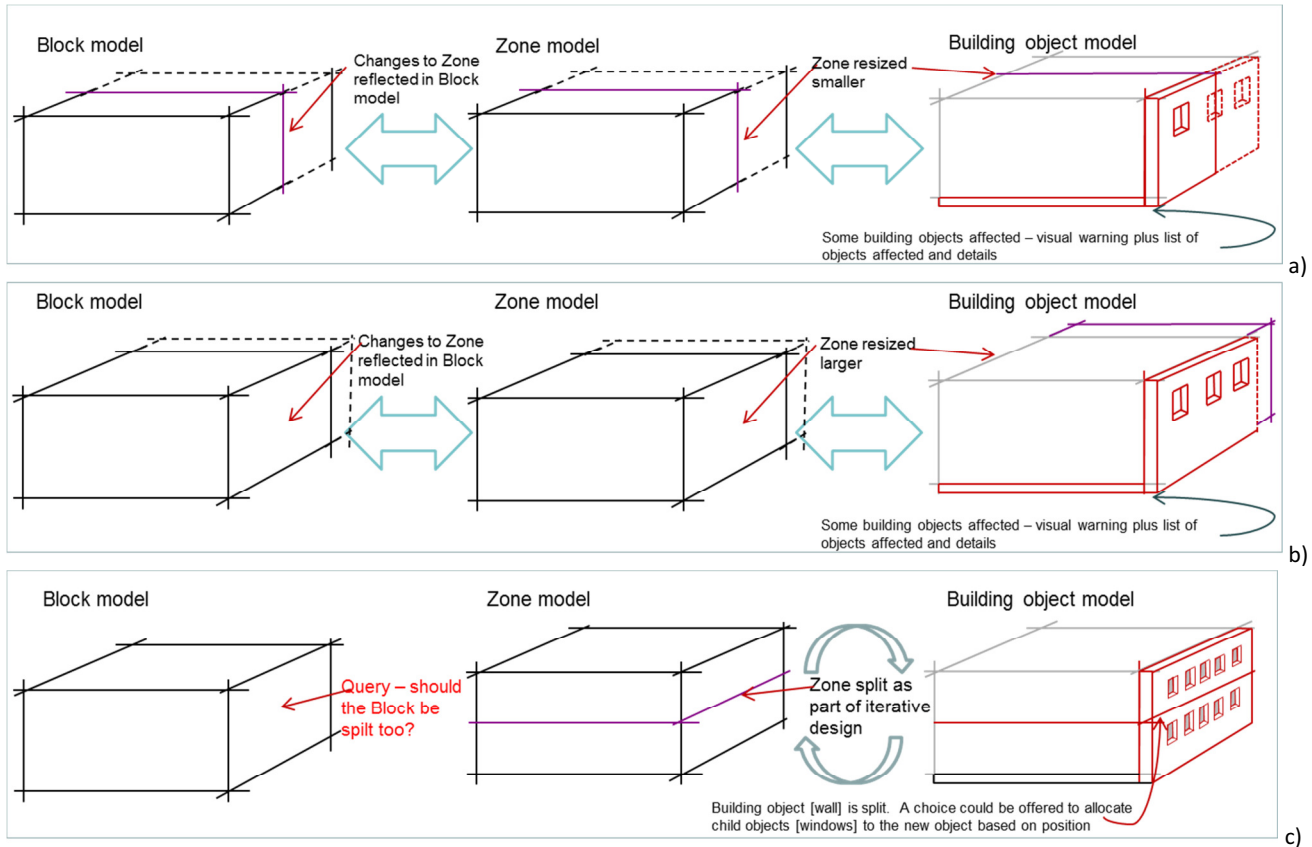
Curves can be an important design feature for architects. Figure 8 illustrates that how a curved element is attached to a zone mesh. It is proposed that curved primitives, such as spheres, cylinders and freeform curves would be available as part of palette of volumes available to the designer in the block and spatial zone modelling phases. However, they would be effectively planar. As buildings objects are attached to the zone surface they could take a curved form as required.

Rules for connections of building objects would be monitored and enforced by the software. The primary rule would be that the zone surfaces would be concurrent, that is neither overlapping or with narrow gaps between them; this is to support reliable thermal analysis and inter-zone heat exchange calculations. All building objects would be positioned in three dimensions within the building model relative to the parent spatial zone. Thus, as part of the iterative design process, if either the block zone, spatial zone or the building object is resized the software will detect the changes. As shown in Figure 9 the objects affected by these changes would then be both highlighted visually in the model and a list of affected objects given. The designer could then deal with the objects as they deemed necessary.

<sup>10</sup> <http://www.ashrae.org/standards-research--technology/standards--guidelines>

<sup>11</sup> <http://www.edsl.net/main/Software/Designer/CIBSE.aspx>

<sup>12</sup> Simulation run in Ecotect

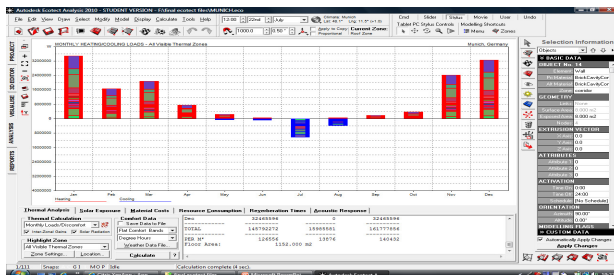


**Figure 9 Block, spaces and detailed models:** a) shows the effect to the model if the space or zone is enlarged, the computer would re-size the block model and the detailed model and give a visual warning as to the building objects affected by the change; b) shows the model expanded and c) shows the zone mesh split with object relocated

The rule for the ‘attachment’ of the building objects to the zone mesh would be established by the software user. For instance, with external walls, there could be a choice between whether the inner face, centre line or outer face of the wall would be coplanar with the zone surface. Objects, such as internal walls, do not need to touch the zone, but their position would be recorded relative the zone in which they are located. Rules or choices for junctions of building objects, such as internal walls joining external walls or the corners of external walls would be provided in a similar way to that already used in BIM software.

Simulation at this stage can include detailed thermal, daylighting, ventilation performance and energy generation characteristics. The model detail required for these types of analysis vary. Thermal simulation is likely to be a full dynamic analysis, taking into account direct and indirect solar gains, internal gains, inter-zonal heat flow, occupancy schedules and internal comfort requirements. Figure 10 shows a typical simulation result illustrating the months where heating or cooling would be required to maintain comfort. At this stage, the space zone mesh will be suitable for inter-zonal studies, but additional data would be required to model solar overhangs and shading devices as shown in Figure 11.

Daylight studies predict the internal natural lighting levels on the working plane or surface to determine if they will be sufficient for occupants of the space to carry out their normal duties. Effective use of natural daylight means that the use of electrical lighting, and hence energy used, can be reduced. Accurate daylight modelling also requires a relatively simple model, however unlike a thermal model, external wall thicknesses, overhangs, light-reflectors and shading devices become important as shown in Figure 11. To enable this type of simulation the automatic generation of an additional mesh would be provided within the software, called the *external envelope*. It would be

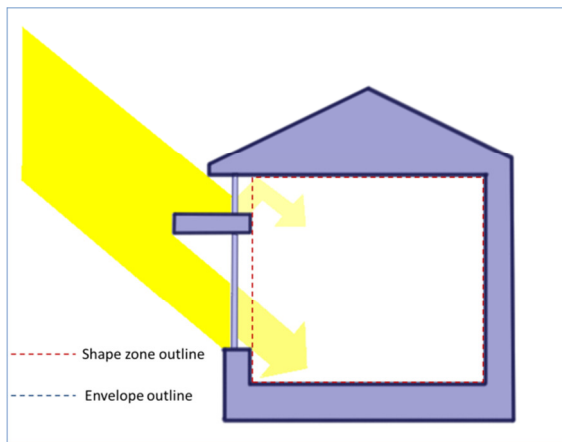


**Figure 10 Showing monthly heating/cooling load for a complete building<sup>13</sup>**

<sup>13</sup>Simulation run in Ecotect



generated from Cartesian coordinates obtained from the zone data and the known thicknesses of the walls and the dimensions of overhangs and shading devices. This mesh would reside on a bespoke layer.



**Figure 11 Showing a diagrammatic section through a building. Penetration of sunlight is restricted by the overhang and the light shelf. Daylight is shown reflected from the light shelf and ceiling**

Ventilation simulation, through the use of CFD, also requires a simplified model. Obstructions, such as internal partitions, and openings, such as windows and louvers, that affect the flow of air are important features to model. This data would also be generated from the geometry of the model and reside on a separate layer.

Detailed predictions would be provided for energy generation by the input of specific materials and product details to the model and the results feed through to the energy goals calculations.

The design advisor would provide typical construction details and the embodied energy of materials along with an option to supply data on local materials (to reduce transport costs). It could provide data and options on how shading could best be provided. The monitoring of goals would be ongoing, but due to the time taken to carry out the more detailed analysis at this stage might be restricted to an overnight run.

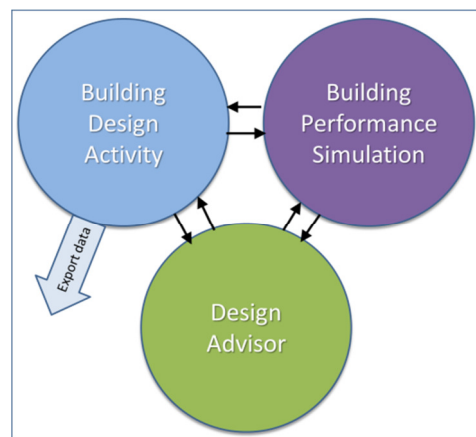
At this detailed design stage the software would provide a range of building model visualisation, rendering and printing options, as typically found in BIM software.

## 5 Discussion and future work

This software concept offers a number of advantages over that currently available. The same model can be used from early sketch design to completion, operation and maintenance. We believe that the early sketch modelling in 3D, through the use of primitive block shapes, should make the software attractive to architects as it could overcome some of the concerns regarding inhibition of early design processes through the use of a high precision tools such as BIM [18]. This sketching of the building form, coupled with rapid 'sketch' type

analysis, should support the architect in the optimisation of both the aesthetics and the performance of the building. It places the determination of the thermal view back into the hands of the architect, who will know the building well, as opposed to an external consultant. Because of this the architect, with the support of the design advisor system, would potentially be better able to conceptualise the building in terms of thermal comfort zones and energy targets. This should partly address concern about 'black box' results where the computer delivers a set of uncomprehensible numbers. Possible adaption to changed climate could also be modelled with the inclusion of future weather data now being developed [19].

It would however restrict the architect to a particular mode of working, in that, as discussed in the paper, the building model has to be assembled in a particular manner. Earlier work suggests that should not be a problem [4] and should reduce anomalies in the building model as reported by Steel et al [20].



**Figure 12 Data flow between the three components of the software, plus the export of data**

Future work falls into three distinct categories; the exchange of data between the three components as shown in Figure 12, the design of the interface and the design of the advisory system.

The combination of the three components of the software, building design, BES and the design advisor relies on the successful exchange of data. The input data for the various BES algorithms and external software would need to be established and cross referenced to check that, in particular, the geometries meet the various requirements. Export and input of data by way of interoperable languages would also require further investigation.

The design of the interface would be challenging as it would need to facilitate the display of the three components: the building model design, input and output information from the BES and information from the design advisor. A particular challenge would be to make the GUI appear simple and intuitive to use and yet provide access to information from detailed simulation results and deliver sophisticated BIM operations.

The design advisor would involve two components; the knowledge base and the goal tracking systems. Compilation of a database that covers an extensive range of subjects such as rules of thumb advice, construction details relative to the geographical location, comfort and user standards and patterns, embodied energy, local and transport details, etc. is a significant and challenging task. In addition it would require constant updating with POE data and new building product details. The goal or target tracking system, linked to the space zones, would require collecting the output from a number of analytical engines to calculate and compare predicted energy required with energy generated, along with warnings on comfort conditions or potential thermal difficulties with the construction.

## 6 Concluding remarks

The challenges facing the construction industry in reducing the energy used by buildings are profound [21][22]. In this paper we have outlined a proposal for software that, whilst alone will not solve these problems, would constitute a valuable tool to support architects to maintain design standards. The proposal is simple, yet novel, to maintain a simple mesh within the building model, denoting zone spaces, through all stages of the design process. The difficulties in creating such software are not in the computational methods involved, but in the scale and size of the undertaking. The development of this type of software will require a large and skilled team.

## 7 Acknowledgements

The authors would like to thank Michael Jackson for his feedback during the development of the ideas presented in this paper and Swanke Hayden Connell Architects for use of the image in Figure 4(c) of the model of the Jennie Lee building.

## 8 References

- [1] Intergovernmental Panel on Climate Change, Climate change 2007 : mitigation of climate change : contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge; New York: Cambridge University Press, 2007.
- [2] Rocky Mountain Institute, Including Building Energy Modeling in the Integrative Design Process. 2011.
- [3] R. Hetherington, R. Laney, and S. Peake, 'Zero and Low Carbon Buildings: A Driver for Change in Working Practices and the Use of Computer Modelling and Visualization', in 2010 14th International Conference Information Visualisation, London, United Kingdom, 2010, pp. 590–596.
- [4] R. Hetherington, R. Laney, and S. Peake, 'Integrated Building Design, Information and Simulation Modelling: The Need for a New Hierarchy', in Building Simulation 2011, Sydney, Australia, 2011.
- [5] J. L. M. Hensen and R. Lamberts, Eds., Building performance simulation for design and operation. Abingdon Oxon; New York NY: Spon Press, 2011.
- [6] S. Attia and A. De Herde, 'Early Design Simulation Tools for Net Zero Energy Buildings: a Comparison of Ten Tools', in Proceedings of Building Simulation 2011, Sydney, Australia, 2011.
- [7] R. J. Hitchcock and J. Wong, 'Transforming Ifc Architectural View Bims for Energy Simulation: 2011', in Proceedings of Building Simulation 2011, Sydney, Australia, 2011.
- [8] J. Clarke, Energy simulation in building design, 2nd ed. Oxford: Butterworth-Heinemann, 2001.
- [9] K. Papamichael and V. Pal, 'Barriers in developing and using simulation-based decision-support software'. Lawrence Berkeley National Laboratory, 2002.
- [10] G. Augenbroe, 'Trends in building simulation', Building and Environment, vol. 37, no. 8–9, pp. 891–902, 2002.
- [11] J. L. M. Hensen, 'Towards more effective use of building performance simulation in design', in Proc. 7th International Conference on Design & Decision Support Systems in Architecture and Urban Planning, 2004, pp. 2–5.
- [12] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors, 2nd ed. Hoboken NJ: Wiley, 2011.
- [13] B. Dong, K. Lam, Y. Huang, and G. Dobbs, 'A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments', in Tenth International IBPSA Conference, Beijing: IBPSA China, 2007.
- [14] S. van Nederveen, R. Beheshti, and W. Gielingh, 'Modelling Concepts for BIM', in Handbook of Research on Building Information Modeling and Construction Informatics, J. Underwood and U. Isikdag, Eds. IGI Global, 2009.
- [15] A. Marsh, 'CAD Geometry vs Performance Analysis, Natural Frequency', Natural Frequency, 2006. [Online]. Available: <http://naturalfrequency.com/articles/cadanalysis>. [Accessed: 24-Aug-2010].
- [16] V. Bazjanac, 'Space Boundary Requirements for Modeling of Building Geometry for Energy and Other Performance Simulation', CIB W78 2010 - Applications of IT in the AEC Industry, 2010.
- [17] V. Bazjanac, 'IFC BIM-Based Methodology for Semi-Automated Building Energy Performance Simulation'. 24-Sep-2008.
- [18] Y. E. Kalay, 'The impact of information technology on design methods, products and practices', Design Studies, vol. 27, no. 3, pp. 357–380, May 2006.
- [19] M. Eames, T. Kershaw, and D. Coley, 'On the creation of future probabilistic design weather years from UKCP09', Building Services Engineering Research and Technology, vol. 32, no. 2, pp. 127–142, Oct. 2010.
- [20] J. Steel, R. Drogemuller, and B. Toth, 'Model interoperability in building information modelling', Softw Syst Model, Oct. 2010.
- [21] T. Oreszczyn and R. Lowe, 'Challenges for energy and buildings research: objectives, methods and funding mechanisms', Bldg. Res. & Info., vol. 38, no. 1, pp. 107–122, Jan. 2010.
- [22] Department for Business, Innovation and Skills, 'Low Carbon Construction'. HM Government, 2010.